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# Eco-Driving Versus Green Wave Speed Guidance for Signalized Highway Traffic: A Multi-Vehicle Driving Simulator Study

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## Abstract

New in-vehicle systems provide the driver with speed advises through the variable message signs and the use of an in-car display. In this paper, two dynamic speed guidance strategies (green wave speed guidance strategy (GWSGS) and eco-driving speed guidance strategy (EDSGS)) through in-car display were tested. A new multi-vehicle driving simulator platform taking into account drivers interactions was built, and the two strategies for highway system were programmed through the script language provided by Virtools software. To evaluate the effectiveness of the overall strategies, 15 typical drivers were recruited to take part in the speed guidance experiments. It was found that the number of stops is both significantly reduced for the vehicles with the GWSGS and EDSGS. Compared with the vehicles without speed guidance, the fuel consumption and CO<sub>2</sub> emissions can be reduced by 25% and 13% under the EDSGS and GWSGS respectively. The eco-driving vehicle's velocity trajectory is smoother than that of the green wave vehicle, and the average compliance rate of EDSGS is higher than GWSGS. The EDSGS showed more benefits than the GWSGS.

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**Keywords:** Highway; Dynamic speed guidance; Green Wave; Eco-Driving; Driving Simulator.

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## 1. Introduction

As a traditional traffic management method, the arterial coordinated control is to ascertain the offset between the neighbouring intersections, according to an assumption of the traffic flow speed. However, in the process of operation, constraints from filed conditions, such as oversized spacing between adjacent intersections, complicated traffic composition and the diversity of driving behaviour, have decreased the reliability and stability

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of the coordinated signal control system, which result in a discrete form of platoon and a large difference between the running speed and the pre-set one. In such cases, signal coordination cannot reach the expected effectiveness. Obviously, a major reason can be attributed to a lack of information about the “future” state of traffic signal resulting in increased fuel consumption, trip time, and engine and brake wear.

Recently, the Connected Vehicle technology initiative by the U.S. Department of Transportation has been impelled into planning and implementation (Research and Innovative Technology Administration, 2012), which makes it not far-fetched today to get real-time vehicle positions and the timing of the traffic signals at downstream. After these information is processed, the in-car display systems can be applied to providing real-time speed advice to the driver by using V2I (vehicle-to-infrastructure) communication capabilities, which enables to achieve an expected driving style.

By sharing a similar way of thought, we developed two dynamic speed guidance (DSG) strategies in this study. The first strategy is that vehicle travels through intersections without stops as possible as it can, and we call it green wave speed guidance strategy (GWSGS). The other one helps yield the most fuel/emission-optimal speed profile for a vehicle approaching several signalized intersections, and we call it eco-driving speed guidance strategy (EDSGS). Thus, the vehicle can be driven at its optimal speed while travelling through several signalized corridors without stopping or using an eco-friendly driving style, based on real-time speed advice. A new multi-vehicle driving simulators platform taking into account drivers interactions was built, and the two individual strategies for highway system were programmed through the script language provided by Virtools modelling software. To determine the effectiveness of the overall strategies, 15 typical drivers took part in the driving simulator studies.

## 2. Literature Review

### 2.1. Previous research into DSG strategies study

Several researchers have developed and studied variable speed algorithms for arterial traffic. Marchau (2010) and Jiménez (2008) oriented towards giving optimal speed advice to the drivers in order to improve safety by taking into consideration the current weather conditions, road grade, etc. Abu-Lebdeh (2010) used dynamic speed control to guide drivers on their best speed selection to improve operation of signalized networks, protecting the congested road network from breakdown. Yang (2010) and Mandava (2009) developed arterial velocity planning algorithms that give dynamic speed advice to individual driver so that the probability of having a green light is maximized and the vehicle will pass through signalized intersections without coming to a stop. To the best of our knowledge, using real-time signal information to forecast the influence of aforementioned external factors and predict a fuel/emission-optimal strategy is still lack of attention. Barth (2011) developed a dynamic eco-driving velocity planning algorithm towards minimizing acceleration/deceleration rates and reducing fuel consumption and emissions. It is expected the vehicle with adaptive cruise control system will adjust its velocity while traveling through a signalized corridor. Rakha (2011) presented seven cases with different speeds and throttles through a sample scenario including just one signalized intersection. After assuming or calculating other parameters for a reasonable setting value, they compared which case has the most fuel optimal speed profile. Sun (2013) developed a dynamic eco-driving speed guidance strategy, which highlights the importance of retaining microscopic fuel consumption models in the optimization function and in a predictive manner to minimize fuel consumption and CO<sub>2</sub> emissions for a given road topography.

The display medium of DSG strategies could be either variable message signs or in-vehicle devices. In-vehicle devices are necessary for GWSGS or EDSGS to provide customized speed guidance to individual drivers.

## 2.2. Assessment of DSG system

The DSG system consists of drivers, vehicles, driving environment, and speed guidance strategies, etc. It involves complex psychological and physical factors. Speed guidance experiment methods include: computer simulation experiments (Abu-Lebdeh, 2010; Yang, 2010), field experiments (Boriboonsomsin, 2011), and virtual reality experiments by driving simulator (Driel, 2007; Duivenvoorden, 2008). Computer simulation experiments are mainly based on micro-simulation software. It is very difficult to describe the influence of driver's psychology and behavior stimulated by the dynamic speed information, so it may cause the experiment results distortion. Field experiments are restrained by the actual scene and economic and time cost, and it is difficult to ensure safety.

Virtual experiment method with its many advantages has become a popular experiment method to study the driving behavior in recent years. Driving simulators enable higher sensing accuracy, like determining the precise position of the car. Moreover, systems and situations that do not yet exist in the real world can be easily simulated before they are introduced into the real world. Finally, simulating potentially dangerous situations is safer than driving in a real environment.

Traditional studies focus on researching the driving behavior, using single driving simulator (Bella, 2008). Some literatures involving multi-vehicle systems, just one vehicle is controlled by the participating driver, other vehicles in the scene are "model car", such as literature (Driel, 2007; Duivenvoorden, 2008). We decided to conduct the experiments in the multi-driving simulators because we were investigating systems in a traffic flow situation that did not yet exist and the experiment could create potentially dangerous situations due to unknown effects on workload.

## 3. Methodology

### 3.1. DSG strategies

We developed two individual DSG strategies for signalized highway corridors in this study: GWSGS and EDSGS. Vehicles being driven on the road segment will receive a speed advice every certain time or distance interval. At every renewal moment, signal timing parameters (cycle, green start time and green end time), vehicle's location, speed and power performance as well as road topology are acquired as the inputs of system calculation model. Then, speed guidance strategies are successively generated for every vehicle based on optimal speed algorithm.

#### 3.1.1. GWSGS

The objective of GWSGS is to guide as many vehicles as possible traveling through intersections without stops as possible as it can. As illustrated in Fig. 1, in normal condition, the discrete and random arrival of vehicles results in inevitable stops at the intersection. To eliminate them, the guided speed is released to the vehicles upstream the intersection. Among all the vehicles supposed to stop, some (red trajectories) pass with acceleration before the green end of earlier cycle, while others (blue trajectories) pass with deceleration after the green start of later cycle.

Four modes of guidance results are generated by system calculation model at renewal moment for every vehicle according to its spatial-temporal trajectories, which are passing with high speed, passing with acceleration, passing with deceleration and passing without guidance. After receiving a speed guidance advice, vehicle compares it to the current velocity. Vehicle execution model decides whether to maintain guidance strategy or abandon it during the renewal interval. A detailed description of the GWSGS is described in the literature (Yang, 2010).

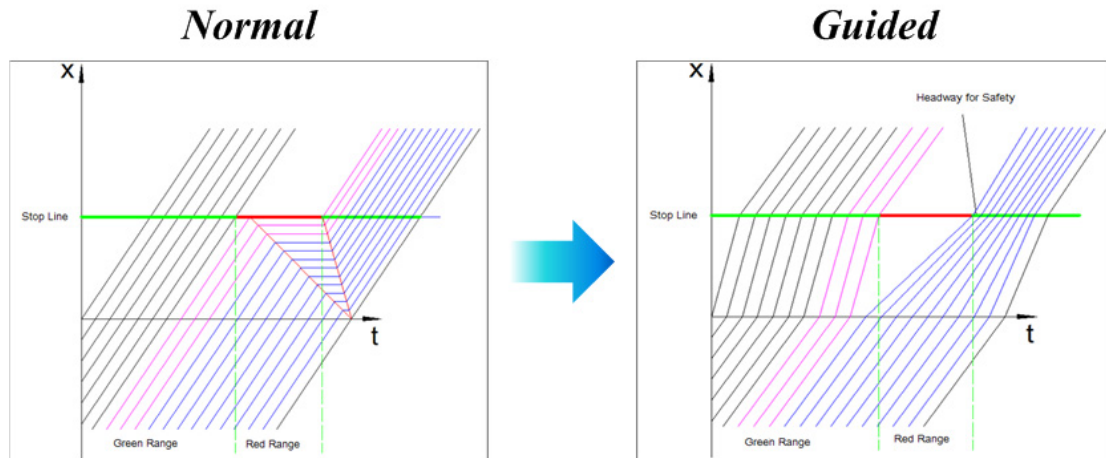


Fig. 1. Trajectory comparison of GWSGS objective

The GWSGS was realized in Virtools program model (Dassault Systemes, 2006), as shown in Fig. 2. *Op1* Building Block (BB) monitors vehicle's positions and *Op2* BB is to monitor the signal phase and timing information of the downstream intersection. Through a series of Op BBs of basic mathematical operations, get a parameter into the *Threshold* BB and compared with the preset threshold. When the vehicle can be driven in a green wave at the maximum limited speed, the *Text Display2* BB gives advice: passing with high speed directly. Otherwise, a series of modules and signal timing information for basic operations calculate a guided velocity again, the value is outputted by *Text Display1* BB.

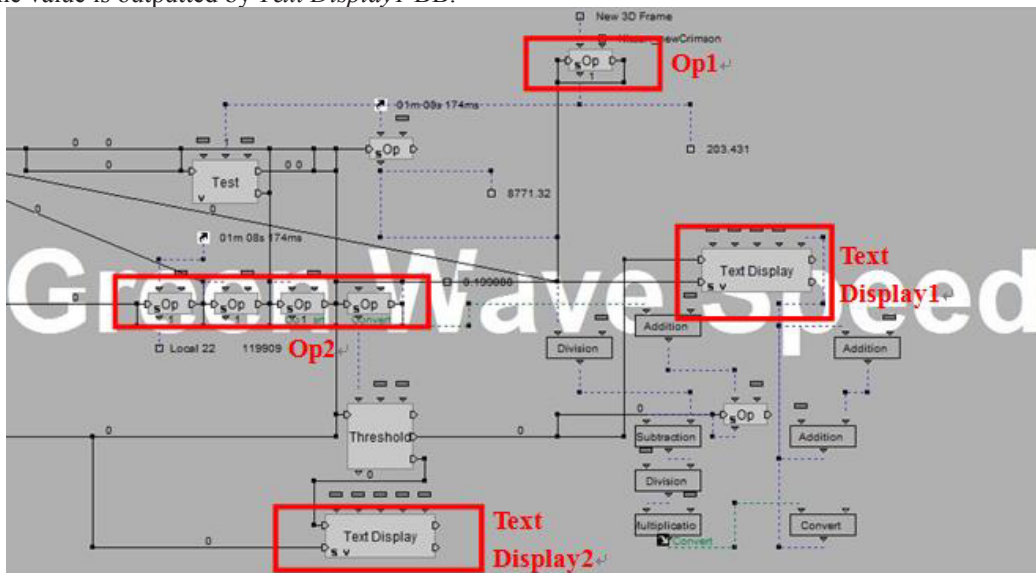


Fig. 2. GWSGS script in Virtools

### 3.1.2. EDSGS

The EDSGS consists of optimization module and ecological index calculation module. The guided velocity is dynamically adjusted based on the vehicle's spatial-temporal trajectories, in relation to which an optimization-based rolling horizon and a dynamic programming approach were adopted. Given the topological information and driving characteristics of testing vehicles, the ecological index calculation module can estimate the fuel consumption rates based on the vehicle operating conditions. Then the optimization module is applied to find an optimal control plan minimizing the total fuel consumption and CO<sub>2</sub> emissions while satisfying the preset minimum and maximum vehicle speed levels.

As shown in Fig. 3, as a vehicle reaches one guided position, the optimization module will calculate fuel consumption along the travelling segment by taking into account all the possible combinations of guided velocity over one optimization distance ( $d_0$ ). After comparing total fuel consumption of each combination, the “guided velocity ribbon” will be determined of the least fuel consumption, as illustrated by the green solid line in Fig. 3. The speed advice provided by the guided position is real-time, based on the vehicle's current velocity, signal phase and timing information, and the distance to the next downstream intersection. If the driver doesn't follow the guidance, he/she will receive a new speed advice at the next guided position. A detailed description of the EDSGS is described in the literature (Sun, 2013).

The EDSGS scripts in Virtools similar to those of the GWSGS, for the paper length limit, we will not explain them here.

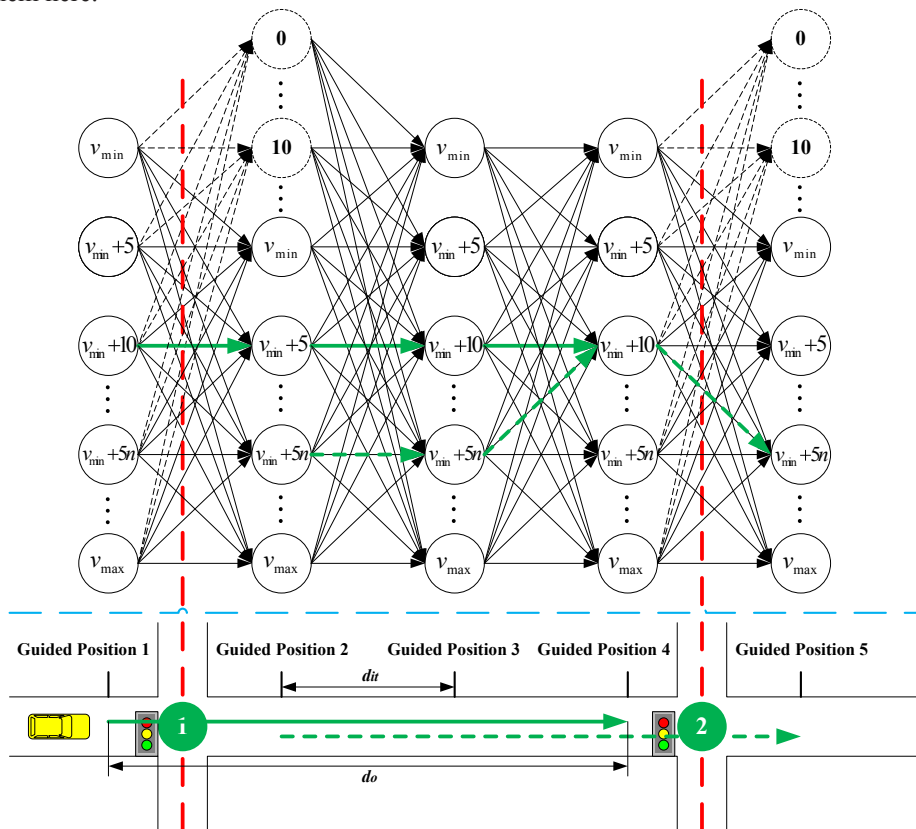


Fig. 3. The EDSGS calculation using dynamic programming diagrams



### 3.2. Research design

A repeated measures design with DSG strategies (without speed guidance versus with GWSGS or EDSGS) as within-subject factor was used. To avoid order and learning effects, the conditions were counterbalanced by a Latin square design. Each driver will complete three experiments in 2 hours.

### 3.3. Scenarios

A section of Cao'an Highway near Tongji University, Shanghai, China is selected as the testbed of initial development base. The experiment section is 1700 m long, with eight lanes in two directions. As illustrated in Fig. 4, two adjacent signalized intersections are included. The distance between them is 1200 m with part of curve segment in the middle. In addition, complicated traffic composition including large amounts of heavy trucks and buses, a pre-set green-wave speed is almost unable to be kept with large speed variance in traffic flow. So vehicles usually have to wait for the green signal in the downstream intersection.

In the experiment, drivers traveled from point A to point D. In order to eliminate the additional errors, such as start, stop, and unskilled operation, only the data collected between point B (50 m from the downstream Lianqun Road) and point C (100 m from the downstream Xianghuang Road) were taken as valid.



Fig. 4. Google map of a part of Cao'an Highway

The other parameters e.g. traffic demand, traffic composition and link capacity were collected with field survey. In all simulations, the test vehicles' mass are all assumed to be 1365 kg, maximum speed limit of all segments is 80 km/h while the minimum is set to be 40 km/h considering the fact that it is hard for driver to obey if the guided velocity is lower than 40 km/h.

### 3.4. Driving simulator

The experiments were conducted in the program-oriented multi-vehicle driving simulators. Each computer was equipped with a special steering wheel, gear, pedals and other hardware devices.

3ds Max and Virtools modeling software were used to build the virtual driving scenes, as shown in Fig. 5 (a). The virtual driving scenes contain three parts of the vehicles, roads, and controller. The controller connected to the simulator hardware, through the BB of Virtools to control the running of the vehicle, enabling the driver through the manipulation of the physical hardware of the steering wheel and pedals to control the vehicle in the virtual scenes. The two speed guidance strategies were programmed through secondary development of the script language provided by Virtools.

In this paper, by the Virtools modeling software, we developed this multi-driving experiment platform that allows drivers to use a number of driving simulators to control multiple vehicles in the same scene for interactive driving, as shown in Fig. 5 (b).



(a) Scene screenshot



(b) Multi-vehicle driving experiments

Fig. 5. Multi-vehicle driving simulator experiments

### 3.5. Participants

15 typical male drivers from Tongji University and nearby community were recruited to take part in the experiments. The age of the participants was between 21 and 50 and shows normal distribution. All the participants had holden their driving licenses for more than five years and drove more than 8,000 kilometers annually.

### 3.6. Procedure

To make the experimenters have more realistic personal experience and acquire richer experiment data, three experiment steps were designed. Firstly, by playing the video of the actual traffic flow and presentation materials of the experiment section before the formal experiment, the participants were familiar with experiment scene and immersed in the experiment environment. Then preliminary experiments were implemented for three rounds, making the participants familiar with the experiment platform and other control equipment. Finally, each participant was numbered and then started the formal experiment.

The participants did driving experiment all in the three scenarios: vehicles without speed guidance, vehicles with GWSGS and vehicles with EDSGS. Each scenario is simulated twenty-four times, and the same experiment repeated four times for each experimenter.

In order to eliminate the effects of cumulative fatigue on the driver produced by repeated experiments, each experiment scene (i.e., the starting positions of vehicles, signal timing parameters) are slightly different (i.e., there are four starting positions (A1, A2, A3, A4) in the same strategy scenario and the vehicle were randomly starting from a different starting position).

### 3.7. Data Collection

The experiment data came from two parts: one part was collected by questionnaires, used to analysis of effectiveness of the driving simulator experiment; the others were output by the driving simulator with a frequency of 0.1 second. These data including time, vehicle position coordinates (x, y), current velocity and guided velocity, which were used to analyze the changes in driving behavior and the effectiveness of the speed guidance strategies.

## 4. Results

### 4.1. Analysis of Effectiveness of the Driving Simulator Experiment

At the end of the preliminary experiment, participants were asked to complete a questionnaire about the virtual vehicle controllability, their driving feelings and attitudes towards the experiment platform. Some of the results are presented in Fig. 6. The questionnaire is designed on a 10-point scale. 10 shows the fully consistent with the reality, and 0 indicates completely inconsistent.

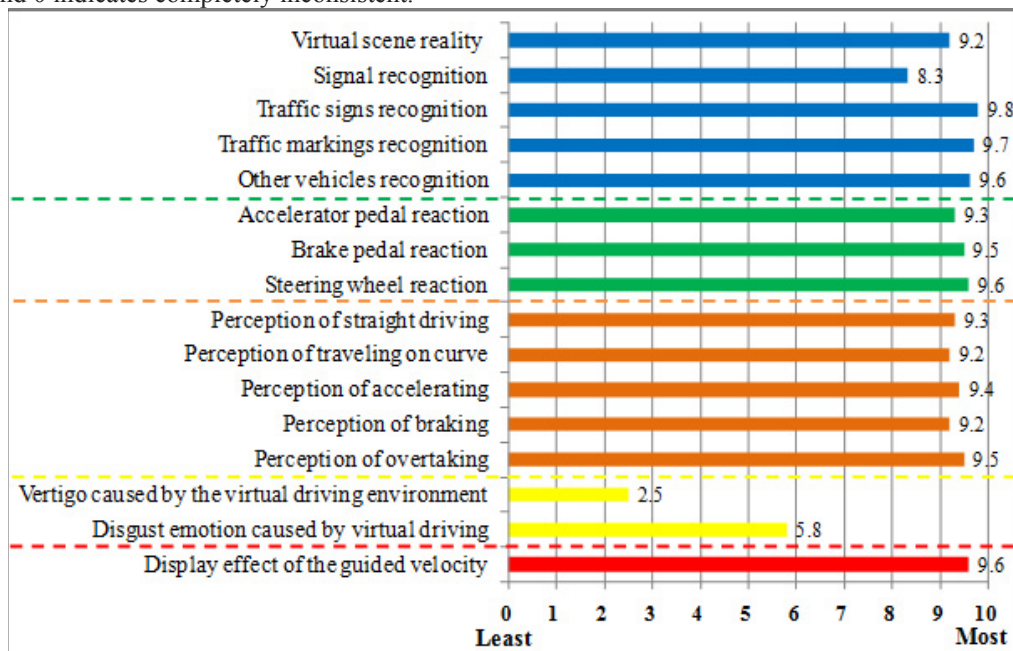


Fig. 6. Participants' responses regarding the driving simulator experimenters



According to the survey responses, the experiment scene has a higher matching degree with the actual (mean score of 9.3). Experimenters can get a good perception of traveling, accelerating, braking and overtaking by manipulating the corresponding equipment, and vehicles can truthfully movement (mean score of 9.5). The display effect of the guided velocity is perfect (mean score of 9.6), but three participants suggested that a voice prompt would be better. The mean score is 4.2 on the aspect of vertigo and disgust caused by virtual driving, indicating that experimenters reject the driving simulator to some extent. Compared to the real driving, if the driving purpose is not clear, simulator driving will be more boring. Therefore, for the same participating driver, the experiments should not be repeated too much.

Overall, the program-oriented multi-driving simulator can be a perfect substitute for field experiments. The experiment data can be expressed relative effectiveness of different experiment scenarios.

#### 4.2. Performance Evaluation

The 3rd vehicle of the platoon was taken all in the three scenarios: vehicles without speed guidance, vehicles with GWSGS and vehicles with EDSGS. The example of these vehicles' velocity profile is shown in Fig. 7 (a). The vehicle with either green wave or eco-driving speed guidance has a much smoother velocity trajectory, resulting in lower fuel consumption, as shown in Fig. 7 (b). Zero portions of the velocity profile show that the vehicle stopped with hard braking at red signals. By predictive use of signal information, the guided vehicle schedules its velocity based on the guided velocity and thus the vehicle can pass through intersections without stop.

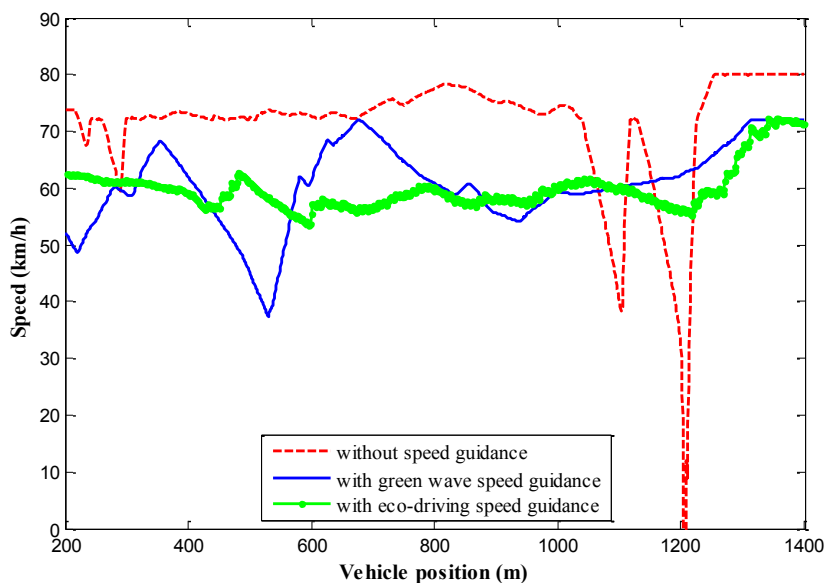


Fig. 7. (a) Velocity profiles for the three vehicles under different scenarios

Fig. 7 (b) illustrates the instantaneous fuel rate comparison for the three vehicles under different scenarios. Without speed guidance, vehicles on the segment were drove randomly, and had to stop in the downstream intersection at a 60% possibility. Too much acceleration and deceleration operation cost a lot of fuel. The fuel rate curve is flat with speed guidance, rising only at the position where the new speed advice is updated.

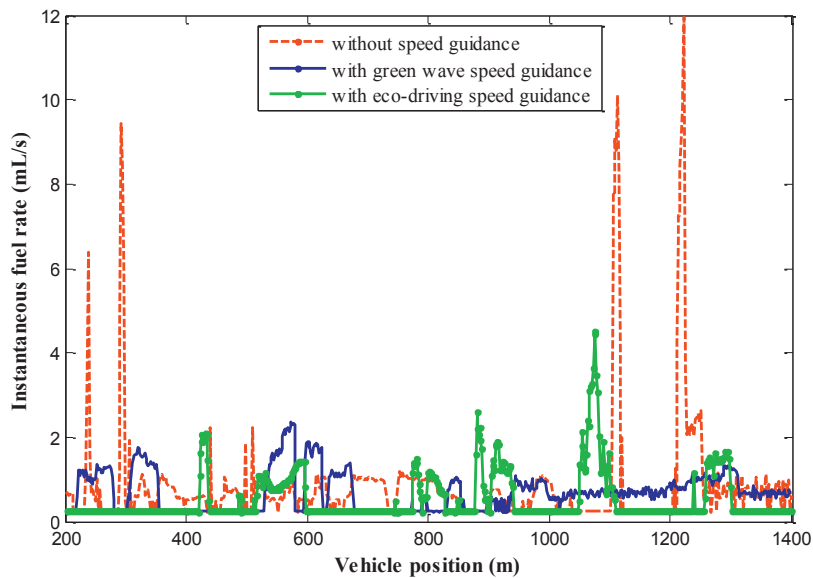


Fig. 7. (b) Instantaneous fuel profiles for the three vehicles under different scenarios

Fig. 7 (a) and 7 (b) also show that the eco-driving vehicle's velocity profile is smoother than that of the green wave vehicle and the eco-driving vehicle's instantaneous fuel rate are mostly the lowest on this road segment. The objective of the two speed guidance strategies is different.

For comparison purposes, the travel time, number of stops, fuel consumption and CO<sub>2</sub> emissions were selected as four evaluation indexes. Fig. 8 provides the comparison results among the vehicles without speed guidance, with GWSGS and with EDSGS. The results for three cases are given in terms of the average value of all vehicles' velocity profiles in the scenarios.

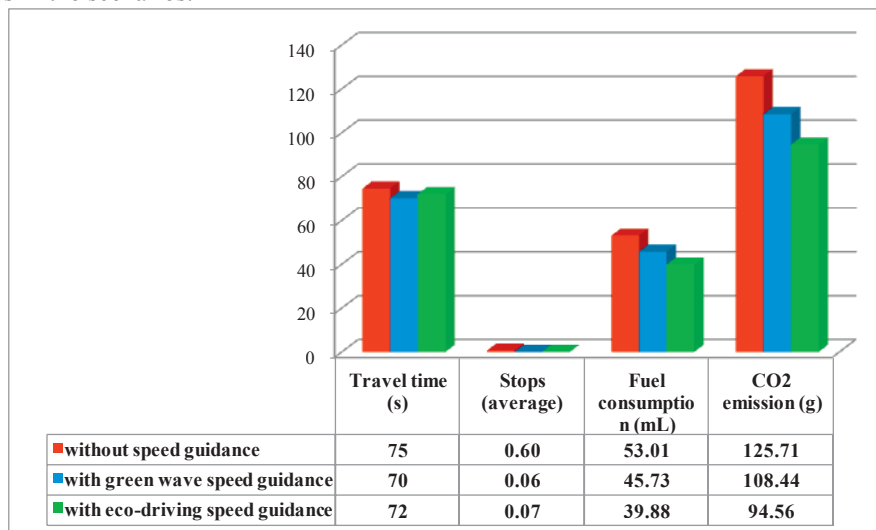


Fig. 8. Evaluation indexes comparison for per vehicle in three scenarios

As shown in Fig. 8, main findings are as following: 1) for the vehicles with and without speed guidance, the travel time has no significant changing. 2) Both the GWSGS and EDSGS have a huge improvement of the stops at downstream intersections. The GWSGS has a little better stopping performance than the EDSGS, but the difference is small. 3) Compared with the Non-speed guidance vehicles, the total fuel consumption is reduced from 53.01 mL to 39.88 mL of about 25% lower and CO<sub>2</sub> emissions are reduced from 125.71 g to 94.56 g of about 25% lower by the EDSGS. The total fuel consumption and CO<sub>2</sub> emissions are only reduced by 13% compared with the Non-speed guidance vehicles.

## 5. Discussion

Speed support for green wave and eco-driving resulted in a change in driving behavior compared to the baseline condition. The participants responded to the speed advice by driving at a speed close to the guided velocity. The average compliance rate of EDSGS is higher than GWSGS. According to the survey responses, we concluded the reasons as follow. 1) The pursuit and trust degree of EDSGS is higher. Relative to the travel time and number of stops, drivers are more inclined to adopting a more fuel-efficient driving style in the future. 2) The values difference between pre and post eco-driving guided velocity is smaller, so drivers are easy to operate. 3) The driver can subjectively judge whether the vehicle will travel through the next intersection with stop or not, but cannot determine which driving style is the most fuel optimal. So drivers have a higher trust on the EDSGS.

Main findings regarding the two speed guidance strategies are as following: 1) The objective of GWSGS is to guide as many vehicles as possible traveling through intersections with no stop and less delay, but results show very little difference in the overall travel time compared to the baseline condition (i.e. Vehicles without speed guidance). 2) For the vehicles with EDSGS, it can be seen that significant fuel savings and emissions reductions, the number of stops obviously reduced compared with the vehicles without speed guidance as well. 3) GWSGS and EDSGS neither drastically affected overall travel time. This conclusion has also been confirmed in the literature (Mandava, 2009; Barth, 2009).

The developed multi-vehicles driving experiment platform has overcome the shortcomings of the traditional driving simulator, which can be manipulated by only one participating driver, and it permits up to 32 drivers coordinating driving in the same scene. The existence of a lead car and traffic follow can simulate the interactional driving behaviors, which weakened the benefits of speed guidance strategies. In these cases, drivers had to give up following the guided velocity in order to guarantee a safe distance to the preceding vehicle. The driving simulator in (Duivenvoorden, 2008) could not measure a change in this case, because it was not possible to distinguish whether the participant was driving freely or was being affected by the lead car. But in this paper, we can do it by means of the collected data, which includes position coordinates of the guided vehicle and the preceding vehicle, current velocity of the guided vehicle and the preceding vehicle, and guided velocity of the guided vehicle.

With the two speed guidance strategies, traffic efficiency has been improved and energy-saving and emission-decreasing effect has a remarkable results. Thus far this has been evaluated under low density traffic conditions. In subsequent work, it is planned to expand this research by evaluating under heavier traffic conditions. In addition, field real vehicle tests are also required to validate these findings.

## 6. Conclusions

Base on the earlier theoretic study, two dynamic speed guidance (DSG) strategies for signalized highway corridors were integrated into the new developed multi-vehicles driving simulator experiment platform. To evaluate the effectiveness of the overall strategy, 15 typical drivers were recruited to take part in the experiments using the multi-vehicle driving simulator. The main conclusions obtained in this study are summarized as follows:

- Both the GWSGS and EDSGS had huge decrease of stops at downstream intersections. However, the travel time has no significant improvement.
- The EDSGS showed a remarkable effect on energy-saving and emission-decreasing. It was found that fuel consumption and CO<sub>2</sub> emissions can be reduced by 25% compared with unguided scenarios.
- The eco-driving vehicle's velocity profile is smoother than that of the green wave vehicle, and the average compliance rate of EDSGS is higher than GWSGS.
- Overall, the EDSGS showed more benefits than the GWSGS. The field tests need to be investigated in the future.

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